Joint space time block code and modulation classification for MIMO systems

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Joint Space Time Block Code and Modulation Classification for MIMO Systems

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***Abstract*—Non-cooperative identification of unknown communication signals is a popular research area with widespread civilian and military applications. Multiple Input Multiple Output (MIMO) systems employing multi-antenna transmission pose new challenges to the signal identification systems, such as the classification of the employed space time block code (STBC) and the modulation in presence of the self-interference inherent to the multi-antenna transmission. In the existing literature, these two classification problems have been handled separately, despite the fact that they are interrelated. This work presents a novel approach to MIMO signal identification by considering the modulation type and the STBC classification tasks as a joint classification problem.**

***Keywords*—MIMO, signal identification, modulation type classification, space time block code classification**

I. Introduction

Non-cooperative identification of unknown communication signals finds application in both military and commercial contexts, such as in electronic warfare, radio surveillance, spectrum monitoring and cognitive radio. Signal identification for multiple input multiple output (MIMO) systems presents new challenges, which do not exist for conventional single input-single-output (SISO) systems, such as the classification of the employed space time block code (STBC). Furthermore, modulation classification (MC) algorithms designed for SISO systems assuming the presence of a single modulated signal at the receiver, are unable to classify MIMO signals, where multiple signals, one from each transmit antenna, are present at each antenna at the receiver [1].

In the existing literature, STBC and modulation classification for MIMO systems are handled as separate problems, despite the fact that these two tasks are fundamentally interrelated. Likelihood based (LB) methods for MC in the literature decide for the modulation that maximizes the likelihood function of the received signal, requiring a-priori knowledge on the employed STBC. In [2] such algorithms are proposed for MIMO systems with spatial multiplexing (SM). In [3], these LB algorithms have been extended to STBC-MIMO signals under the assumption that the employed STBC and the code timing, i.e. the beginning of each coded signal block, are known at the receiver. Feature based (FB) MC algorithms for SM signals can be found in [4], [5] and [6], in which modulation specific features based on higher order cumulants are employed. MIMO modulation classification in absence of a-priori information on the employed STBC, however, is an open problem currently unexplored in the existing literature.

Similarly, LB STBC classification methods in the literature assume the presence of perfect knowledge on the employed modulation, the SNR and code block timing [7]. Their FB counterparts usually exploit the cyclostationary behavior of the received signal induced by the coding operation, which has the benefit of not requiring any a-priori information on the modulation type, however, they are sub optimal [8], [9], [10].

The interdependence between the MC ans STBC classification tasks is due to the fact that the likelihood function of the received signal in a MIMO system depends jointly on both the modulation and the STBC. Hence, an optimal classification in a realistic non-cooperative scenario where both are unknown can only be achieved by considering these two problems jointly. Recognizing this interdependence, this work proposes, for the first time in the literature, a novel LB approach to the MIMO signal identification problem, where the modulation type and the STBC employed in a MIMO signal are jointly classified. In addition to providing an optimal approach to the MIMO signal identification problem as a whole by formulating it as a joint classification problem, the proposed method, for the first time in the literature, enables modulation classification in absence of a-priori information on the STBC employed in the transmission.

First, the optimal joint classifier is presented, where the channel matrix, noise variance and the block timing are assumed to be known a priori. Subsequently, classifiers for more realistic scenarios are introduced, where some or all of these parameters are unknown. The proposed joint classification algorithms are evaluated via simulations, and compared with a more conventional sequential classification approach, where the STBC classification is performed prior to the modulation classification, providing the modulation classifier with the required information on the employed STBC.

II. System Model and Assumptions

We consider a MIMO transmitter with n_t transmit antennas where the k'th transmit signal block of size $n_t \times L$ can be written as $\mathbf{X}[k] = \mathbf{C}(\mathbf{s}[k])$ with the modulated information bearing signal vector $\mathbf{s}[k] = [s_1[k], \ldots, s_{N_c}[k]]^T$ of length N_c, and the STBC operation $\mathbf{C}()$ with a code duration of L. Note that spatial multiplexing (SM), where the modulated data is directly multiplexed into transmit antennas is considered as a special case of STBC with $\boldsymbol{C}(\boldsymbol{s}[k]) = \boldsymbol{s}[k]$. Assuming a MIMO receiver with n_r antennas, the k'th receive signal block of size $n_r \times L$ $\mathbf{Y}[k]$ is given as:

$$\mathbf{Y}[k] = \mathbf{H}\mathbf{X}[k] + \mathbf{W}[k] \,, \tag{1}$$

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where $\mathbf{W}[k]$ is the circular complex additive white Gaussian noise matrix with variance σ^2, and $\mathbf{H}$ is the $n_r \times n_t$ channel matrix whose elements are modeled as independent zero-mean circular complex Gaussian random variables with unit variance. We assume a flat block fading channel over the observation interval.

The aim of this work is to perform the joint classification of the modulation type and the STBC employed in a MIMO system using the received signal block $\boldsymbol{Y} = [\boldsymbol{Y}[0], \ldots, \boldsymbol{Y}[N/L-1]]$ of size $n_r \times N$, where N is the length of the observation interval. The study is restricted to the general class of linear and memoryless modulations and linear STBCs. It is assumed that the set of possible modulation types $\mathcal{M} = \{M_1, \ldots, M_P\}$ with P elements and the set of possible codes $\mathcal{C} = \{\mathbf{C}_1, \ldots, \mathbf{C}_Q\}$ with Q elements are known to the classifier. The joint classification is performed within the set $\Theta = \mathcal{M} \times \mathcal{C}$ which contains PQ hypotheses.

III. Classification Algorithm

This work proposes a LB approach to the joint classification problem. Assuming that the transmit signal employs the modulation type M_j and the STBC $\mathbf{C}_i$, and the code block timing τ (i.e. the beginning of each coded signal block) is known, the average likelihood function of the received signal block $\mathbf{Y}$ of length N can be calculated by averaging the likelihood function of $\mathbf{Y}$ over all $(K_{M_j})^{N_c}$ possible modulated data vectors $\mathbf{s}^{(j)}$ for the modulation type M_j [3]:

$$\Lambda(\mathbf{Y}|\mathbf{H}, \sigma^2, \mathbf{C}_i, M_j, \tau) = \frac{1}{(K_{M_j})^{Nr_{c_i}}(\pi\sigma^2)^{n_r}} \times \prod_{k=0}^{(N/L_i-1)} \sum_{\mathbf{s}^{(j)} \in M_j} \exp\left(\frac{-1}{\sigma^2}||\mathbf{Y}[k] - \mathbf{H}\mathbf{C}_i(\mathbf{s}^{(j)})||_F^2\right) \quad (2)$$

where K_{M_j} is the number of discrete states in the modulation type M_j, L_i is the length and r_{c_i} is the code rate of $\mathbf{C}_i$ and $||.||_F$ represents the Froebenius norm. The proposed optimal joint classifier for the modulation type and STBC is obtained by jointly maximizing the natural logarithm of the average likelihood function wrt the modulation type and the STBC i.e.

$$(\hat{M}, \hat{\mathbf{C}}) = \underset{M_j \in \mathcal{M}, \mathbf{C}_i \in \mathcal{C}}{\arg\max} \{\log \Lambda(\mathbf{Y}|\mathbf{H}, \sigma^2, \mathbf{C}_i, M_j, \tau)\}. \quad (3)$$

This classifier, which we refer to as the joint average likelihood ratio (J-ALRT) classifier, can be considered as optimal in the Bayesian sense, given that the channel matrix $\mathbf{H}$, the noise variance σ^2 and the code block timing τ, are known; hence, its performance can be regarded as an upper performance bound for the joint classification problem considered in this work. In many practical scenarios involving signal classification, no cooperation between the transmitter and receiver is possible, thus these parameters are usually unknown to the receiver. For such practically more relevant cases, we propose a joint hybrid likelihood ratio test (J-HLRT) which approximates, for each hypothesis, the average likelihood function in (3) by substituting the actual values of the channel matrix and the noise variance with their blind estimates, i.e. :

$$(\hat{M}, \hat{\mathbf{C}}) = \underset{M_j \in \mathcal{M}, \mathbf{C}_i \in \mathcal{C}}{\arg\max} (\log \Lambda(\mathbf{Y}|\hat{\mathbf{H}}^{(i,j)}, \hat{\sigma}^2_{(i,j)}, \mathbf{C}_i, M_j)), \quad (4)$$

where $\hat{\mathbf{H}}^{(i,j)}$ and $\hat{\sigma}^2_{(i,j)}$ are the blind estimates of $\mathbf{H}$ and $\sigma^{\mathbf{2}}$ respectively, generated with the assumption that the modulation M_j and the STBC $\mathbf{C}_i$ have been transmitted.

1) Estimation of the channel matrix: The blind channel estimation strategy employed in this work consists of two steps. First, the higher order statistics (HOS) based MIMO blind channel estimation algorithm proposed in [11] is used, which can be employed for a large set of codes, including SM, orthogonal, quasi-orthogonal and non-orthogonal STBCs, to form a pre-estimate of the channel matrix. Subsequently, the channel ambiguities that may have remained are removed by using a blind phase estimation algorithm if necessary. For a detailed derivation and analysis of the algorithm, the reader is referred to [11]. It should be noted that, while independent of the modulation type, the estimation requires the knowledge of the STBC used in the signal, thus, the pre-estimate $\tilde{\mathbf{H}}^{(i)}$ is generated for each hypotesized STBC $\mathbf{C}_i \in \mathcal{C}$ individually. Furthermore, the pre-estimate contains STBC-specific ambiguities, which, for a large class of codes, have been derived and listed in [11]. Amongst the STBCs considered in this work, which are given in the Appendix, only SM and the Alamouti code lead to phase and permutation ambiguities. It is straightforward to show that the permutation ambiguities are not relevant to the classification, leaving only the phase ambiguities to be resolved. For the remaining codes, there solely exist a sign ambiguity, which does not have any effect on the classification due to the symmetry of the employed modulation types, thus, for these STBCs, the pre-estimate of the channel matrix can be used directly, i.e. $\hat{\mathbf{H}}^{(i,j)} = \tilde{\mathbf{H}}^{(i)}$. For SM and the Alamouti code, the generation of $\hat{\mathbf{H}}^{(i,j)}$ requires the estimation and correction of the phase offset terms in the corresponding phase ambiguity matrices.

2) Blind Phase recovery for SM and the Alamouti Code: For the case of SM, eq. (2) reduces to

$$\mathbf{y}[k] = \mathbf{H}\mathbf{s}[k] + \mathbf{w}[k]\,, \quad (5)$$

where $\mathbf{y}[k]$ is the k'th received signal vector. We employ a phase offset estimation strategy similar to those in [5]. We first recover an estimate of the transmit signal vector $\mathbf{s}[k]$ using the pre-estimate of the channel matrix $\tilde{\mathbf{H}}^{(i)}$, i.e.

$$\tilde{\mathbf{s}}[k] = (\tilde{\mathbf{H}}^{(i)\dagger}\tilde{\mathbf{H}}^{(i)})^{-1}\tilde{\mathbf{H}}^{(i)\dagger}\mathbf{y}[k]. \quad (6)$$

Due to the phase ambguities in the channel estimation, the components of $\tilde{\mathbf{s}}[k]$ are noisy and phase-rotated versions of the components of the actual transmit signal $\mathbf{s}[k]$:

$$\tilde{s}_l[k] = e^{j\varphi_l}s_l[k] + v_l[k] \quad (7)$$

where $v_l[k]$ is a noise term and φ_l is a random phase offset, which can now be estimated with the assumption that the modulation M_j has been transmitted. As in [5] and [2], we employ the blind phase recovery in algorithm in [12] exploiting the higher order moments of the signal. With the assumption that M_j has a $\frac{2\pi}{V_j}$ rotationally symmetric constellation, the phase offset estimate is given as

$$\hat{\varphi}_l^{(j)} = \frac{1}{V_j}\arg(\mu_j^{(V_j)}\sum_{k=1}^{N}\tilde{s}_l[k]^{V_j}), \quad (8)$$

where $\mu_j^{(V_j)} = E\{(s_j^*)^{V_j}\}$ is the V_j'th order moment of a unit power signal using the modulation M_j. After estimating the phase offset for each component of $\tilde{\mathbf{s}}[k]$, the phase corrected channel estimate for the modulation M_j can be expressed as $\hat{\mathbf{H}}^{(i,j)} = \tilde{\mathbf{H}}^{(i)}\hat{\mathbf{\Phi}}^{(i,j)}$, where $\hat{\mathbf{\Phi}}^{(i,j)}$ is an $n_t \times n_t$ diagonal matrix with elements $[\hat{\mathbf{\Phi}}^{(i,j)}]_{l,l} = e^{-j\hat{\varphi}_l^{(j)}}$. The phase ambiguity matrix for the case of the Alamouti code is similar to that of SM, except the fact that the two phase offsets are related to each other [11]. Thus, a similar phase recovery procedure can be employed for Alamouti coded signals.

3) Estimation of the noise variance: The blind channel estimation algorithm in [11] is based on the assumption of unit power transmit signal components and employs this as a constraint in solving the cost minimization problem. Thus, it is straightforward to show that, for all the modulation types and the STBCs considered in this work, a method-of-moments estimator for the noise variance can be given as

$$\hat{\sigma}^2_{(i,j)} = \frac{1}{n_t} trace\Big((\hat{\mathbf{H}}^{(i,j)})^\dagger \hat{\mathbf{H}}^{(i,j)}(\hat{\mathbf{\Sigma}} - \mathbf{I})\Big) \quad (9)$$

where $\hat{\mathbf{\Sigma}} = \frac{1}{N}\sum_{k=0}^{N-1} \tilde{\mathbf{s}}[k]\tilde{\mathbf{s}}^\dagger[k]$ is the sample covariance matrix of the transmit signal recovered with the channel estimate $\hat{\mathbf{H}}^{(i,j)}$.

4) Classification in absence of the code block timing information: For the most general case, where the code block timing τ is also unknown, a decision theoretic approach is formulated by realizing that for $\mathbf{C}_i \in \mathcal{C}$, it can only take on a finite number of discrete values within the set $\mathcal{T}_i = \{0, \ldots, L_i - 1\}$. Thus, the J-HLRT algorithm is extended for this case by maximizing (4), for each hypothesis C_i, with respect to the unknown block timing parameter $\tau \in \mathcal{T}_i$:

$$(\hat{M}, \hat{\mathbf{C}}) = \underset{M_j \in \mathcal{M}, C_i \in \mathcal{C}, \tau \in \mathcal{T}_i}{\arg\max} (\Lambda(\mathbf{Y}^{(\tau)} | \hat{\mathbf{H}}^{(i,j)}, \hat{\sigma}^2_{(i,j)}, \mathbf{C}_i, M_j, \tau)), \quad (10)$$

where $\mathbf{Y}^{(\tau)}$ is the received signal block which has been parsed with the assumption of the code block timing τ.

IV. Classification Results

In this section, the proposed joint classification algorithms are evaluated using simulations. We consider the set of possible modulation types $\mathcal{M} = \{BPSK, QPSK, 8PSK, 16QAM\}$. Two sets of possible STBCs is considered. For $n_t = 2$, we consider the set $\mathcal{C}^{(2)} = \{SM^{(2)}, \mathbf{C}_{AL}\}$ and for $n_t = 3$, $\mathcal{C}^{(3)} = \{SM^{(3)}, \mathbf{C}_1, \mathbf{C}_2\}$, where $SM^{(n_t)}$ represents SM with n_t transmit antennas. (See the Appendix for the code matrices of $\mathbf{C}_{AL}, \mathbf{C}_1$ and $\mathbf{C}_2$). For n_t=2, the classification is performed within the set $\Theta^{(2)} = \mathcal{M} \times \mathcal{C}^{(2)}$, with 8 hypotheses, whereas for $n_t = 3$, the set $\Theta^{(3)} = \mathcal{M} \times \mathcal{C}^{(3)}$ with 12 hypotheses is considered. For each hypothesis, 1000 Monte Carlo trials have been performed. We use the average probability of correct joint classification P_{cc} as a performance measure, which, with the assumption of equiprobable hypotheses is given as

$$P_{cc} = \frac{1}{|\mathcal{M}||\mathcal{C}|} \sum_{j=1}^{|\mathcal{M}|} \sum_{i=1}^{|\mathcal{C}|} P[(\hat{M}, \hat{\mathbf{C}}) = (M_j, \mathbf{C}_i) | (M_j, \mathbf{C}_i)], \quad (11)$$

with $P[(\hat{M}, \hat{C}) = (M_j, \mathbf{C}_i) | (M_j, \mathbf{C}_i)]$ the probability of correct joint classification of the modulation M_j and STBC C_i.

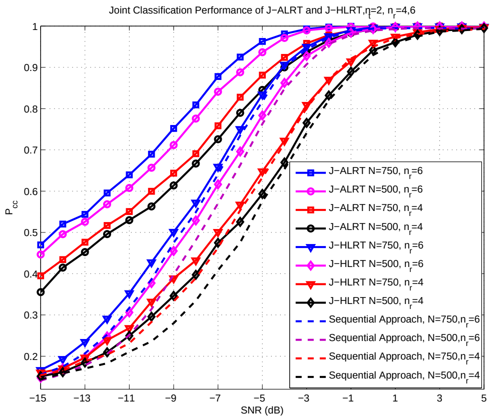

Fig. 1: Classification performance: J-ALRT of eq. (3), J-HLRT (4) and t

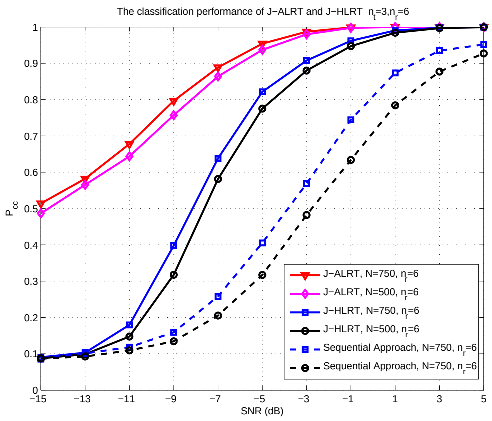

Fig. 2: Classification performance: J-ALRT of eq. (3), J-HLRT of eq. (4) and the sequential approach for $\Theta^{(3)}$, $n_r = 6$.

Figures 1 and 2 display the performance of the proposed J-ALRT and J-HLRT classifiers given in eqs. (3) and (4), for the sets of hypotheses $\Theta^{(2)}$ with $n_r = 4, 6$, and for $\Theta^{(3)}$ with $n_r = 6$ respectively. The classification has been performed for $N = 500$ and 750. Clearly, the use of the blind estimates of the channel matrix and noise variance in the J-HLRT instead of their true values leads to a considerable decrease in the classification performance compared to the ideal J-ALRT. As expected, the performance increases as the number of observed vector samples N and the number of receive antennas n_r increase. Both for $\Theta^{(2)}$ and $\Theta^{(3)}$, the proposed joint classifiers exhibit a high classification performance even in the low SNR regime. Furthermore, in both figures, the performance of the proposed joint classification approach is compared with a conventional sequential method, where the STBC classification is performed prior to the modulation classification, providing the modulation classifier with the information on the employed STBC. Since this approach can only be used with a sub optimal STBC classification method that does not require the modulation type of the transmit signal, we use the cyclostationarity based classification approach in [10] for the set of codes $\mathcal{C}^{(2)}$ and $\mathcal{C}^{(3)}$ respectively. The subsequent modulation classification is performed by maximizing the likelihood function in (4) only wrt. the modulation type, using the STBC information from the previous step. While this sequential method exhibits a considerably lower computational complexity, the results show

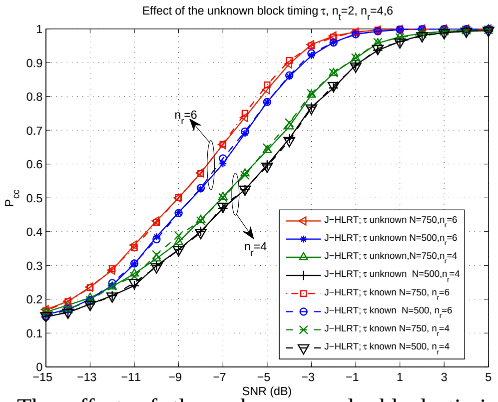

Fig. 3: The effect of the unknown code block timing on the performance of the J-HLRT classifier for $\Theta^{(2)}$, n_r=4,6.

that the proposed joint approach outperforms the sequential method in all cases, and the performance gap increases with increasing n_t and decreasing N.

Figure 3 illustrates the practically most relevant scenario where, in addition to $\mathbf{H}$ and σ^2, the code block timing τ is also unknown to the receiver. The classification is performed using eq. (10) for $n_t = 2$, $n_r = 4, 6$ for the set of hypotheses $\Theta^{(2)}$, and the results are compared with the case of known τ (4). Clearly the proposed approach in eq. (10) is able to handle the lack of the block timing information without any essential decrease in the performance. It should be noted, however, that this approach leads to a considerable increase in the computational complexity, since the maximization is to be performed for each possible value of τ for each $\mathbf{C}_i \in \mathcal{C}$.

V. Conclusion

This paper presents a novel approach to the signal identification problem for MIMO systems by considering the classification of the modulation type and the STBC as a joint classification problem, in contrast to the existing literature, where these two problems are considered separately. This approach, for the first time in the literature, enables MIMO modulation classification in absence of the a-priori knowledge of the employed STBC. First, an optimal LB joint classifier is presented, which considers the ideal but unrealistic scenario, where the channel matrix, the noise variance and the code block timing are known to the receiver, whose performance can be considered as an upper bound to the joint classification problem. Subsequently, suboptimal J-HLRT classifiers are proposed for practically more relevant cases, where some or all of these parameters are unknown. The numerical results show that the proposed algorithms exhibit good classification performance for relatively low values of SNR, and outperform a more conventional sequential approach. Future work will include the extension of this method to fast fading channels.

Appendix
The STBCs Considered for Classification

The joint classifiers proposed in this paper can be used for any linear modulation and any linear STBC. In the simulations, we have limited ourselves to cases with $n_t = 2$ and $n_t = 3$. For $n_t = 2$, the set of considered STBCs is $\mathcal{C}^{(2)} = \{SM^{(2)}, \mathbf{C}_{AL}\}$, where $SM^{(n_t)}$ represents SM with n_t transmit antennas and $\mathbf{C}_{AL}$ is the well known Alamouti code given in [13]. The set of STBCs considered for $n_t = 3$ is $\mathcal{C}^{(3)} = \{SM^{(3)}, \mathbf{C}_1, \mathbf{C}_2\}$, where the code matrices of $\mathbf{C}_1$ [14] and $\mathbf{C}_1$ [15] are given as:

$$\mathbf{C}_1 = \begin{bmatrix} s_1 & -{s_2}^* & \frac{s_3^*}{\sqrt{2}} & \frac{s_3^*}{\sqrt{2}} \\ s_2 & s_1^* & \frac{s_3^*}{\sqrt{2}} & \frac{-s_3^*}{\sqrt{2}} \\ \frac{s_3}{\sqrt{2}} & \frac{s_3}{\sqrt{2}} & \frac{-s_1 - s_1^* + s_2 - {s_2}^*}{2} & \frac{s_2 + s_2^* + s_1 - {s_1}^*}{2} \end{bmatrix}, \quad (12)$$

$$\mathbf{C}_2 = \begin{bmatrix} s_1 & 0 & s_2 & -s_3 \\ 0 & s_1 & s_3^* & s_2^* \\ -{s_2}^* & -s_3 & s_1^* & 0 \end{bmatrix}. \quad (13)$$

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